Beyond single-photon localization at the edge of a Photonic Band Gap.

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We study spontaneous emission in an atomic ladder system, with both transitions coupled near-resonantly to the edge of a photonic band gap continuum. The problem is solved through a recently developed technique and leads to the formation of a "two-photon+atom" bound state with fractional population trapping in both upper states. In the long-time limit, the atom can be found excited in a superposition of the upper states and a "direct" two-photon process coexists with the stepwise one. The sensitivity of the effect to the particular form of the density of states is also explored.

I. INTRODUCTION

The emergence of materials with photonic band gaps (PBG) [1,2], also referred to as photonic crystals, has stimulated a broad range of problems pertaining to the interaction of few-level atoms with unusual (structured) reservoirs. The unconventional photonic density of states (DOS) associated with such materials leads to a number of novel effects which pose severe demands on the theoretical tools necessary for their prediction and/or interpretation. Certain basic issues related to such problems are encapsulated in the behavior of excited atomic states with transition frequencies around the edge of the DOS. Even the decay of an excited two-level atom (TLA) has been shown to exhibit novel behavior under such circumstances, the most notable aspect of which is the formation of the so-called "photon+atom" bound state (PABS) [3–5]. Even in the context of this simple arrangement, however, it has been difficult to handle the problem of more than one photon in the PBG reservoir. An approach capable of surmounting this limitation has been presented recently in the context of a TLA and shown to provide the solution to the problem of the coupling of a TLA to both a PBG reservoir and a defect mode [6].

For a number of reasons, three-level atoms are of particular interest in quantum optics and predictably their behavior in the context of structured reservoirs has been addressed. This includes ladder, lambda and V-type arrangements [7–11]. Mathematical difficulties, however, have limited the relevant investigations to the case of only one photon present in the structured reservoir. This is indeed rather limiting as to the scope of questions one is allowed to contemplate.

It is our purpose in this paper to show how our approach provides a way out of this limitation. Any of the above mentioned standard three-level systems can be addressed. We have chosen the present results on the ladder system which in open space involves a cascade of two photon emissions [12]. As we show in the following sections, allowing both photons to be strongly coupled to the PBG reservoir we obtain what should be called "two-photon+atom" bound state. The formation of such a state is then found to be associated with a counterintuitive coherent evolution of the three atomic states.

The first part of our study has been based on the so-called isotropic model for the DOS of the PBG reservoir [13], which could be argued to effectively reduce the problem to one dimension in wavevector ($\vec{k}$)-space. A rather conspicuous feature of that DOS is a sharp (divergent) peak at the edge of the gap. In order to explore the persistence of our predictions under more relaxed assumptions for the DOS, we have introduced a modified form represented by a generalized Lorentzian profile. It is still isotropic, but it does not exhibit the singularity at the edge. The basic features of the predicted behaviour are still present with only some quantitative modifications.

The paper is organized as follows: Section II contains a description of the system and a brief summary of the discretization method. In section III, we derive the equations of motion for the amplitudes involved in the wavefunction of the system Atom+Continuum, which are solved numerically. The dynamical behaviour of the system is thus investigated. In section IV the same problem is placed in the context of a generalized Lorentzian profile model for the DOS, while the results are summarized in section V.

II. THE SYSTEM

We consider a three level atom in a cascade configuration, with atomic levels $|1\rangle, |2\rangle, |3\rangle$ and energies $\hbar\omega_1, \hbar\omega_2, 0$ respectively, where $(\omega_1 > \omega_2)$ (Fig. 1a). Both atomic transitions are coupled near-resonantly to the edge of a photonic band gap and are thus strongly modified. In the isotropic model and close to the band-edge, the dispersion relation of PBG materials, can be

approximated by the effective mass dispersion relation [13,14]

$$\omega_k \simeq \omega_e + A(k - k_0)^2, \qquad (1)$$

where ω_e, k_0 are the frequency and the wavenumber corresponding to the band-edge and A is a material specific constant. The corresponding density of states (DOS) reads

$$\rho(\omega) = \frac{\rho_o}{\sqrt{\omega - \omega_e}}\Theta(\omega - \omega_e), \qquad (2)$$

where ρ_o is a material specific constant and $\Theta(x)$ the Heaviside step-function.

Neglecting the zero-point energies of the field modes and adopting the rotating wave approximation, the Hamiltonian of the system in the interaction picture ($\hbar = 1$) is written as

$$V = i \sum_\mu g_\mu^{(1)}(a_\mu^\dagger \sigma_{21} e^{-i\delta_\mu^1 t} - a_\mu \sigma_{12} e^{i\delta_\mu^1 t})$$
$$+ i \sum_\lambda g_\lambda^{(2)}(a_\lambda^\dagger \sigma_{32} e^{-i\delta_\lambda^2 t} - a_\lambda \sigma_{23} e^{i\delta_\lambda^2 t}), \qquad (3)$$

where σ_{kl} denote the atomic dyadic operators $|k\rangle\langle l|$ with $k, l \epsilon \{1, 2, 3\}$; $\delta_\mu^1 = (\omega_1 - \omega_2) - \omega_\mu$, $\delta_\lambda^2 = (\omega_2 - \omega_3) - \omega_\lambda$, while $a_\mu, a_\mu^\dagger(a_\lambda, a_\lambda^\dagger)$ are the creation and annihilation operators of the structured continuum, which is coupled to the atomic transitions, via the respective coupling constants $g_\mu^{(1)}, g_\lambda^{(2)}$.

The spectral response $SR(\omega_\mu)$ corresponding to the PBG effective mass dispersion relation Eq. (1) is given by

$$SR(\omega_\mu) \equiv \sum_\sigma \int_0^{4\pi} d\Omega_\mu \rho(\omega_\mu) \left|g_\mu^{(1)}\right|^2 = \frac{\mathcal{C}_1}{\pi} \frac{\Theta(\omega_\mu - \omega_e)}{\sqrt{\omega_\mu - \omega_e}}, \qquad (4)$$

where the sum is over the polarizations, the integral runs over the solid angle and $\mathcal{C}_1$ is the effective coupling of the upper transition to the structured continuum [7].

In order to deal with the double excitation into the structured reservoir, we use the discretization method that we have presented recently [6]. Briefly, we replace the density of modes in Eq. (2) near the atomic transitions (for $\omega < \omega_u$) by a collection of discrete harmonic oscillators, while the rest of the mode-density is treated perturbatively since it is far from resonance. We propagate the total wavefunction (Atom+Modes) to obtain the dynamics of the system.

For an arbitrary DOS, the frequencies of the discrete modes, are obtained through the relation

$$\omega_{j+1} = \omega_{j-1} + 2/\rho(\omega_j), \qquad (5)$$

which for the case of the DOS of Eq. (2) can be reduced to

$$\omega_j = \omega_e + j^2 \delta\omega, \qquad (6)$$

where $\delta\omega$ is chosen sufficiently small ($\delta\omega \approx 4.4 \times 10^{-4} \mathcal{C}_1^{2/3}$). The coupling $\mathcal{G}^{(1)}$ of the upper transition to each one of the discrete modes is found using Eq. (4)

$$\mathcal{G}^{(1)} \approx \sqrt{\frac{2\mathcal{C}_1}{N\pi}} \sqrt{\omega_u - \omega_e}, \qquad (7)$$

where N is the number of discrete modes and ω_u is the upper limit of the discretized part. A similar relation can be derived for the coupling $\mathcal{G}^{(2)}$ of the lower transition, where now $\mathcal{C}_2$ will be the corresponding effective coupling. In general, the dipole moments $\langle 1|d|2\rangle$ and $\langle 2|d|3\rangle$ are different and thus for the rest of this paper we let the couplings $\mathcal{C}_1$ and $\mathcal{C}_2$ be different.

Let us denote by $|3, 1_j, 1_m\rangle$, a state of the combined system (atom+field), where the atom is in state $|3\rangle$ and two photons have been emitted into the structured reservoir, populating the modes j and m respectively. Following this pattern of notation, the wavefunction of the complete system reads

$$|\Psi(t)\rangle = a|1, 0, 0\rangle + \sum_j b_j|2, 1_j, 0\rangle + \sum_{j,m} C_{jm}|3, 1_j, 1_m\rangle. \qquad (8)$$

III. EQUATIONS OF MOTION AND RESULTS

The time dependence of the amplitudes, is governed by the Schrödinger equation and after eliminating the off-resonant modes [6], we find

$$\dot{a} = -i \sum_{\omega_\mu > \omega_u} \frac{\left|g_\mu^{(1)}\right|^2}{\delta_\mu^1} a - \sum_{j=1}^N \mathcal{G}_j^{(1)} b_j e^{i\delta_j^1 t}, \qquad (9)$$

$$\dot{b}_j = -i \sum_{\omega_\lambda > \omega_u} \frac{\left|g_\lambda^{(2)}\right|^2}{\delta_\lambda^2} b_j - \sum_{m=1}^N \mathcal{G}_m^{(2)} C_{jm} e^{i\delta_m^2 t}$$
$$- \sqrt{2}\mathcal{G}_j^{(2)} C_{jj} e^{i\delta_j^2 t} + \mathcal{G}_j^{(1)} a e^{-i\delta_j^1 t}, \qquad (10)$$

$$\dot{C}_{jm} = \mathcal{G}_m^{(2)} b_j e^{-i\delta_m^2 t} + \mathcal{G}_j^{(2)} b_m e^{-i\delta_j^2 t}, \qquad (11)$$

$$\dot{C}_{jj} = \sqrt{2}\mathcal{G}_j^{(2)} b_j e^{-i\delta_j^2 t}, \qquad (12)$$

where j, m are mode indices and for all discrete modes $\mathcal{G}^{(1)} = \mathcal{G}_j^{(1)} = \mathcal{G}_m^{(1)}$ and $\mathcal{G}^{(2)} = \mathcal{G}_j^{(2)} = \mathcal{G}_m^{(2)}$, while the shift terms can be determined, converting the sum into an integral from $\omega = \omega_u$ to infinity.

This set of equations is solved numerically for 150 discrete modes ($\omega_u \approx 10\mathcal{C}_1^{2/3}$), with the results presented in Figs. 2-6. We plot the population in the upper level (solid line), the intermediate level (dashed line) and the lower level (dot-dashed line), for various detunings of the transition frequencies from the band-edge. We define the relative detunings of the upper and lower transitions from

the band-edge as $\delta_{12} = \omega_1 - \omega_2 - \omega_e$ and $\delta_{23} = \omega_2 - \omega_3 - \omega_e$, respectively.

In all figures, we can identify a "transient regime", on a short time scale of the order of $\mathcal{C}_1^{2/3}$, when part of the atomic population is lost. On a longer time scale ("dynamic regime"), the populations in the atomic levels undergo oscillations, strongly dependent on the relative detunings from the band-edge, reflecting the emission and reabsorption of the photon(s). The localization at the atom of the photon emitted in the first transition, is accompanied by emission of a photon in the lower transition, which will be also localized at the atom. In analogy with the case of one photon in a TLA, two photons are now backscattered to the atom after tunneling a characteristic distance and reexcite it.

As is known from the coupling of a TLA to the PBG reservoir, the dressing of the atom by its own radiation causes splitting of the atomic levels. This splitting is sufficiently strong to push one level of the doublets outside the gap and the other inside. The dressed state outside the gap looses all its population in the long-time limit, while the one inside the gap is protected from dissipation and thus is stable. The number of stable localized states, is intimately connected to the behavior of the system in the long-time limit. One such state gives rise to steady state population in the excited level, while two of them lead to an undamped beating of the system between the two non-decaying states [4,5].

For our three-level atom, two transitions are at the edge, and thus more than one stable localized state can be found in the gap. In analogy to the "single-photon+atom" bound state, we have the formation of a "two-photon+atom" bound state, which exhibits population trapping in both excited states, in the long-time limit. Thus, the atom is finally excited, in a superposition of the upper states (Fig. 2). This is a novel behavior, due to the fact that both transitions and not only one, are coupled to the same structured continuum. Note that, even in the case that only the ($|2\rangle \rightarrow |3\rangle$) transition is at the edge of the gap, it is the intermediate level that exhibits non-zero steady-state population but not the upper level [3,7].

In the language of dressed states, the oscillations in the populations of the atomic levels reflect the interference between the dressed states of the atom. We additionally note that the oscillations in the populations of the intermediate and lower level are "in phase". This is a rather surprising result, since one would expect the population in the intermediate state to be maximum when the population in the lower state is minimum and viseversa. The phenomenon is even more pronounced in Figs. 3. After an initial transient regime in which about 15% of the population is lost, the remaining population oscillates between the upper level and the two lower levels, in a non-dissipative way. The undamped oscillations imply the beating of the system, between more than two non-decaying dressed states.

The "in phase" oscillations, stem from the localization of both photons at the site of the atom. The system can make the transitions $|1\rangle \leftrightarrow |3\rangle$ either with a stepwise process ($|1\rangle \leftrightarrow |2\rangle \leftrightarrow |3\rangle$) or with a two-photon process ($|1\rangle \leftrightarrow |3\rangle$). Which of the two routes the system will follow to arrive at $|3\rangle$ depends on the detuning δ_{12}.

Specifically, if the upper transition is outside the gap, whatever the detuning from the edge of the lower transition is, it seems preferable for the system to "decay" via the stepwise process rather than the two-photon process indicated in Fig.4. This is no different from the behaviour of a ladder system in open space. On the contrary, if the upper transition is inside the gap, the system evolves in time as if the upper state were coupled to the intermediate state via a single-photon process, and simultaneously to the ground state via a "direct" two-photon process, with respective frequencies Ω_1 and Ω_2. This can not be anticipated on the basis of the behaviour in open space and it is what we meant by counter-intuitive in the introduction.

To gain further insight into this effect, we can adopt a simple 3-level model without dissipation and assign a single-photon Rabi frequency Ω_1 between $|1\rangle$ and $|2\rangle$ and a two-photon Rabi frequency Ω_2 between $|1\rangle$ and $|3\rangle$ (Fig. 1b). An analysis through standard rate equations shows that the populations of the atomic levels oscillate with the same frequency $\Omega = \sqrt{\Omega_1^2 + \Omega_2^2}$, with the oscillation of the two lower levels being in phase. The ratio of the amplitude of the oscillation of the intermediate level to that of the lower level is related to the ratio of the Rabi frequencies, i.e. Ω_1/Ω_2. In Fig. 3b representing the result of the numerical calculation for the system in the PBG reservoir, we note that the dashed and the dot-dashed lines, corresponding to the populations in the intermediate and ground levels, respectively, are indistinguishable. This implies that the corresponding effective Rabi frequencies Ω_1 and Ω_2 are practically equal. It is the combination of the coupling constants and detunings that conspire to produce that behaviour.

The effective detuning of the $|3\rangle \leftrightarrow |1\rangle$ transitions from the band-edge for the "direct" two-photon process is defined as $\Delta^{(2)} = \omega_1 - \omega_3 - 2\omega_e$. From the known dynamics of a TLA with transition frequency at the edge of the gap, depending on $\Delta^{(2)}$, we may expect suppression or inhibition of the "direct" two-photon process. Specifically, for detunings inside the gap ($\Delta^{(2)} < 0$), the "direct" two-photon emission should be totally or partially suppressed, while for detunings outside the gap and almost at the edge ($\Delta^{(2)} > 0$), it should be enhanced due to the high density of final available states.

For transitions symmetrically placed around the band-edge ($\delta_{12} = -\delta_{23}$), with the upper one being inside the gap ($\delta_{12} < 0$), the detuning for the "direct" two-photon transition is exactly at the edge ($\Delta^{(2)} = 0$) (Fig. 5).

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For the parameters used in Figs. 5 and without taking into account the "direct" two-photon process, the "single-photon+atom" bound state for the upper state should be metastable, in the sense that the main part of the population should be lost in the long-time limit. On the contrary, we find that this does not happen and the part of the population that has not been lost in the transient regime, oscillates between the upper and the ground state. These oscillations are not reflected in the intermediate level's population which remains almost constant with some oscillations of negligible amplitude. This behavior definitely indicates the coupling of the upper level to the ground level via a "direct" two-photon process as described above. Note again the "in phase" oscillations for the two lower levels.

Choosing δ_{23} such that $\Delta^{(2)} > 0$ (Fig. 6), the main part of the population is indeed lost in the long-time limit. The difference between Fig. 5a and Fig. 6 is the detuning of the lower transition from the band-edge. In both cases ($\delta_{23} = 2\mathcal{C}_2^{2/3}$, $\delta_{23} = 4\mathcal{C}_2^{2/3}$), the behavior of a TLA in the long-time limit is the same i.e. the population is lost. For the Ladder system, however, we note an oscillatory behavior where part of the population is trapped to the atom in the long-time limit for $\delta_{23} = 2\mathcal{C}_2^{2/3}$ and complete decay for $\delta_{23} = 4\mathcal{C}_2^{2/3}$. The photon-atom bound state formed due to the upper transition becomes therefore metastable [3,7] as soon as δ_{23} is chosen such that $\Delta^{(2)} > 0$. This is a conclusion that has been checked for various detunings of the atomic transitions from the band-edge but with the upper one always in the gap ($\delta_{12} \leq 0$).

IV. GAP WITH A LORENTZIAN PROFILE OF DOS

The isotropic model for the DOS of a photonic crystal has been employed quite extensively in the literature. That is the model we have employed in the previous sections in order to have a direct assessment of the new results vis a vis those obtained in previous work with only one photon in the reservoir, where the same DOS has been assumed. It is, however, well known that this DOS is somewhat artificial, with a divergence as the frequency approaches the band edge. The infinitely high sharp peak at the edge tends to exaggerate many effects and it is important to check predictions made on the basis of this model against other forms of DOS. With this intention, we introduce here a DOS which although still isotropic, does not exhibit a divergence at the edge.

What is essential for an appropriate model of the DOS is that it exhibit a dip and also that it tend to the open space DOS as the frequency becomes much larger or smaller than the mid-gap frequency. We have chosen to adopt as a model of such a DOS an inverted Lorentzian

of higher order given by the expression

$$\rho(\omega) = \rho_0 \left[1 - \frac{\Gamma^n}{(\omega - \omega_o)^n + \Gamma^n} \right]. \qquad (13)$$

First of all, this DOS approaches the open space value ρ_0 for $|\omega - \omega_o| >> \Gamma$. Second, it does not exhibit a divergence at the edge. In fact, the "edge" is not infinitely steep, but does rise more steeply, as $n \to \infty$.

It could be argued that this DOS does not exhibit a clear edge and possesses a zero only at one point. It should be kept in mind on the other hand that, in a realistic PBG material, the gap does not necessarily mean a true zero but a range of frequencies over which the DOS is several orders of magnitude smaller than that of open space [15]. Taking n sufficiently large, in Eq. (13), one can obtain a range of frequencies over which $\rho(\omega)/\rho_0$ is smaller than a desired value. For $n = 6$, for example, $\rho(\omega)/\rho_0 \leq 10^{-6}$ for $\omega = \omega_o \pm 0.1\Gamma$. One can further combine the inverted Lorentzian with step functions in order to simulate a true zero over a range of ω, if so desired. The shape of the DOS given by Eq. (13), can be viewed as a compromise between the isotropic and the anisotropic models [13], and has been used in the literature for $n = 2$ [14,16,17]. It should be stressed once more that the modified DOS in no way relaxes its isotropic in $\vec{k}$ space nature. It only eliminates the singularity.

We proceed now to the exploration of the ladder system under the DOS of Eq. (13) adopting the specific case of $n = 6$. It is one of the strengths of the technique of discretization that it can be implemented with essentially any DOS, provided the manner of discretization is adapted to the demands of the particular form. For the case under consideration, which is symmetric around ω_o, we chose a range $\omega_{low} < \omega < \omega_{up}$ within which the DOS is replaced by a sufficiently large number (in this case 150) equidistant discrete modes. The spectral response corresponding to Eq. (13) for $n = 6$ is of the form

$$SR^{(1)}(\omega_\mu) = \frac{\gamma_1}{2\pi} \left[1 - \frac{\Gamma^6}{(\omega_\mu - \omega_o)^6 + \Gamma^6} \right], \qquad (14)$$

where γ_1 is the decay rate of the upper state in free space. The coupling of the upper transition to the ith discrete mode is frequency dependent and is given by

$$\mathcal{G}^{(1)}(\omega_i) = \sqrt{\frac{\gamma_1}{2\pi}} \sqrt{\left[1 - \frac{\Gamma^6}{(\omega_i - \omega_o)^6 + \Gamma^6} \right] \Delta\omega}, \qquad (15)$$

where $\Delta\omega \approx 0.27\gamma_2$ is the spacing between two discrete modes and ω_i is the frequency corresponding to the ith mode. An analogous relation gives the coupling of the lower transition, $\mathcal{G}^{(2)}$, to the ith mode, where γ_1 is replaced by γ_2, the free space decay-rate of the intermediate state. By way of comparison illustrating the philosophy of the discretization procedure, note that here the mode-spacing is uniform but the coupling constant

frequency-dependent; while in section II (Eqs. 5 and 7) it is the other way around.

The rest of the mode-density, for $\omega > \omega_{up}$ and $\omega < \omega_{low}$, is treated perturbatively [6] leading to a shift for the two upper levels. These shift terms differ from those in Eqs. (9-12) and are not given explicitly. They can, however, be determined numerically. The relative positions of the upper and lower transition frequencies are now defined with respect to the central frequency ω_o of the gap, in terms of the detunings: $\delta_{12} = \omega_1 - \omega_2 - \omega_o$ and $\delta_{23} = \omega_2 - \omega_3 - \omega_o$, respectively. In Fig. 7, we present the evolution of the population in the states of the Ladder system as a function of time, for a particular combination of detunings. As in the previous figures corresponding to the isotropic model, both upper and lower levels exhibit non-zero steady-state population, as a consequence of the "two-photon+atom" bound state. The oscillations, however, in the atomic populations, which can be interpreted as interference between the dressed states, are not present. It seems that this oscillatory behavior is strongly related to the isotropic model. For the Lorentzian profile, the part of the doublet that is pushed outside the gap, decays much faster than the isotropic model would predict. From this we conclude that in the isotropic model, the "dynamic regime" which follows the initial transient regime and is dominated by the emission and reabsorption of photons, or else the interference between the various dressed states, is much more pronounced than in the Lorentzian model, or we would argue any model that does not exhibit the highly peaked feature of the isotropic model [18]. Without the concentration of the density of states around a peak, the notion of dressed states is diluted. Nevertheless, the coherent superposition of states and the "two-photon+atom" bound state persists even in this model. Atomic populations remain trapped for long times, long compared to $1/\gamma_2$.

A further issue needs to be brought up here, in connection with the time scale of the persistence of any "photon+atom" bound state. As long as the model for the DOS involves an exact zero over some frequency range, the "photon+atom" bound state lives for ever, which mathematically implies a non-zero fractional population trapping in the limit $t \to \infty$. In reality, however, the DOS, more often than not, will not involve an exact zero but a deep minimum, as already mentioned in the beginning of this section. As a result, the life-time of the "photon+atom" bound state, will be long on some time scale but not necessarily for $t \to \infty$ in the mathematical sense. It is this finiteness of the lifetime of the "two-photon+atom" bound state that would cause the populations of states $|1\rangle$ and $|2\rangle$ in Fig.7 to decay to zero, if the calculation were extended to sufficiently long times. The essential point therefore is that the population may remain trapped for such a long time which, for all practical purposes, is equivalent to $t \to \infty$.

V. SUMMARY

We have investigated the dynamics of a Ladder atomic system with both transitions coupled to the same structured reservoir. This has been possible through a discretization approach according to which the density of modes over a range near the atomic transitions is replaced by an appropriately chosen collection of discrete harmonic oscillators, with the rest of the mode-density treated perturbatively. We have found that this system supports a "two-photon+atom" bound state which leads to a fractional population trapping in both of the upper states and the atom can be in a superposition of the upper levels even in the long-time limit. In the presence of the two photons at the site of the atom, we have shown that the atom has two paths for the $|1\rangle \leftrightarrow |3\rangle$ transition, and found that a "direct" two-photon process coexists with a stepwise one. Which of the two dominates is determined mainly by the detuning of the upper transition from the band-edge. We have further explored the persistence of this effect under much more relaxed forms of the DOS and shown that, although quantitatively modified, the basic effect remains.

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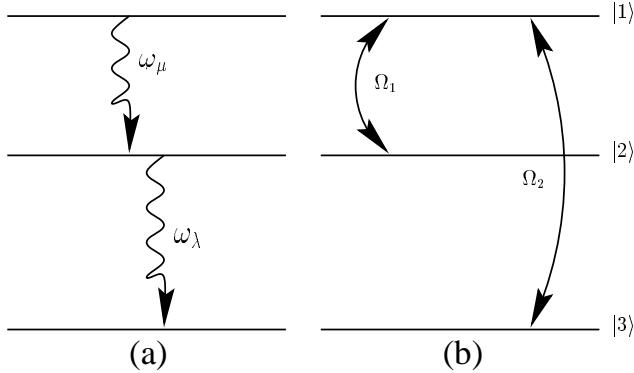
FIG. 1. (a) Schematic representation of the atomic system and the possible transitions. (b) The upper state simultaneously coupled to the intermediate state and the ground state via a single- and two-photon process respectively.
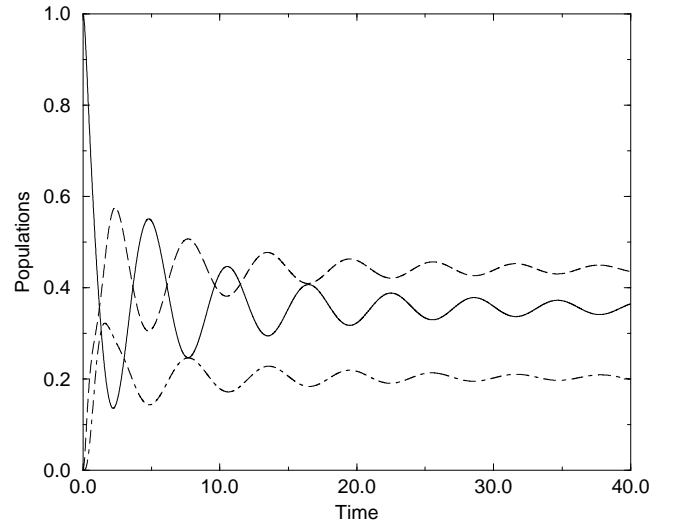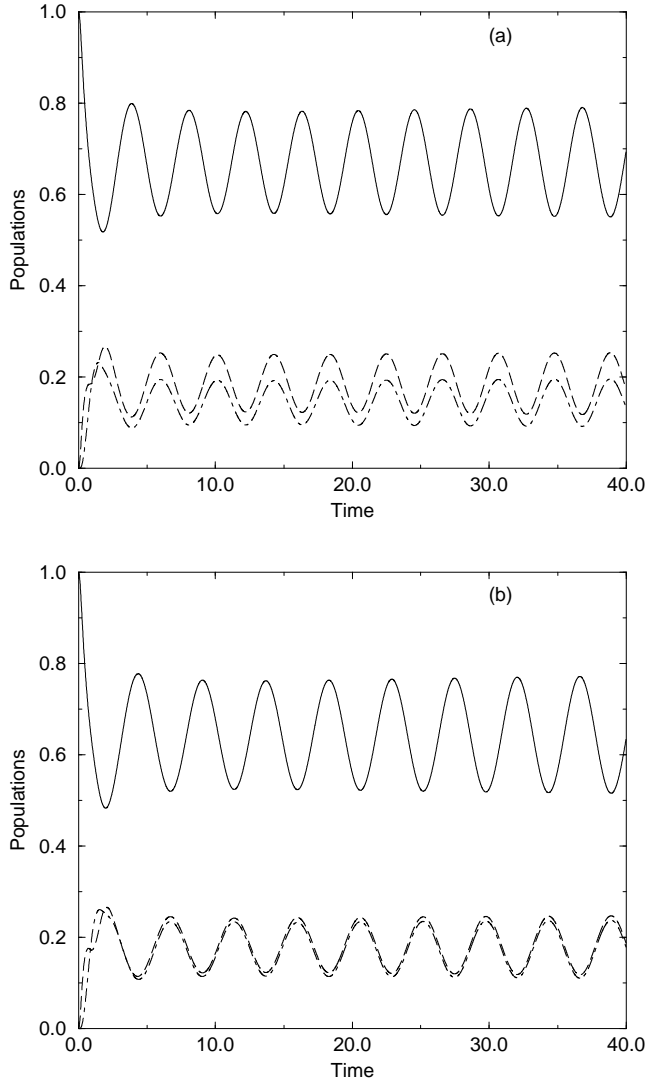

FIG. 2. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\mathcal{C}_2 = 1.5\mathcal{C}_1$, $\delta_{12} = -\mathcal{C}_2^{2/3}$ and $\delta_{23} = 0$. The time is in units of $\mathcal{C}_1^{2/3}$.
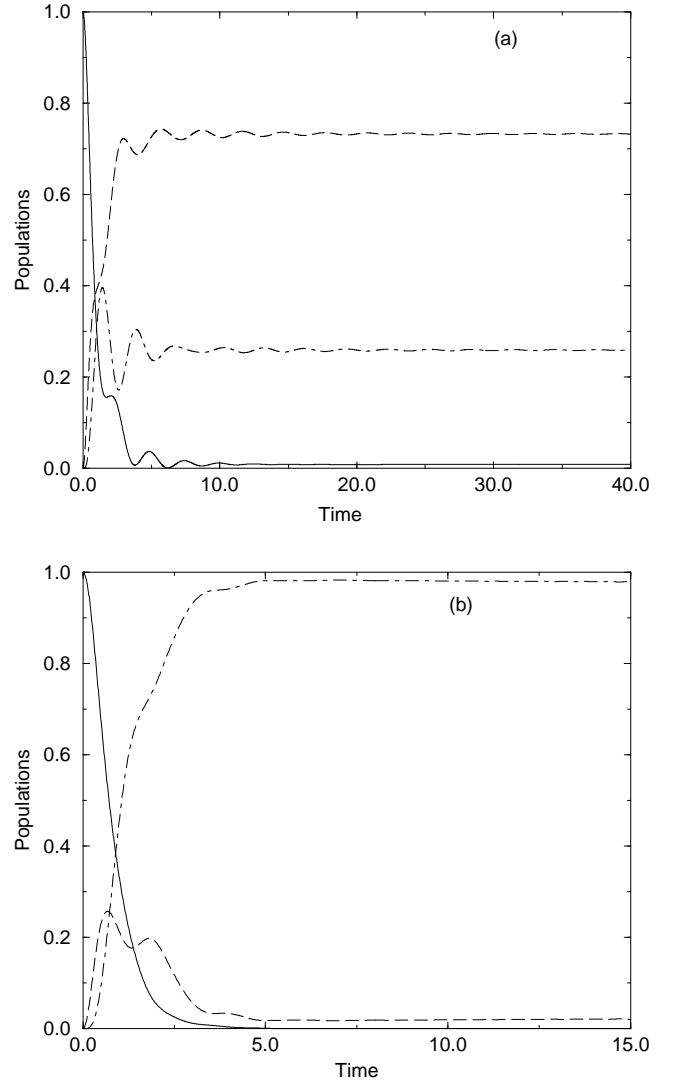
FIG. 3. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\mathcal{C}_2 = 1.5\mathcal{C}_1$, (a) $\delta_{12} = -2\mathcal{C}_2^{2/3}$ and $\delta_{23} = 1\mathcal{C}_1^{2/3}$; (b) $\delta_{12} = -2\mathcal{C}_2^{2/3}$ and $\delta_{23} = 1\mathcal{C}_2^{2/3}$. The time is in units of $\mathcal{C}_1^{2/3}$.
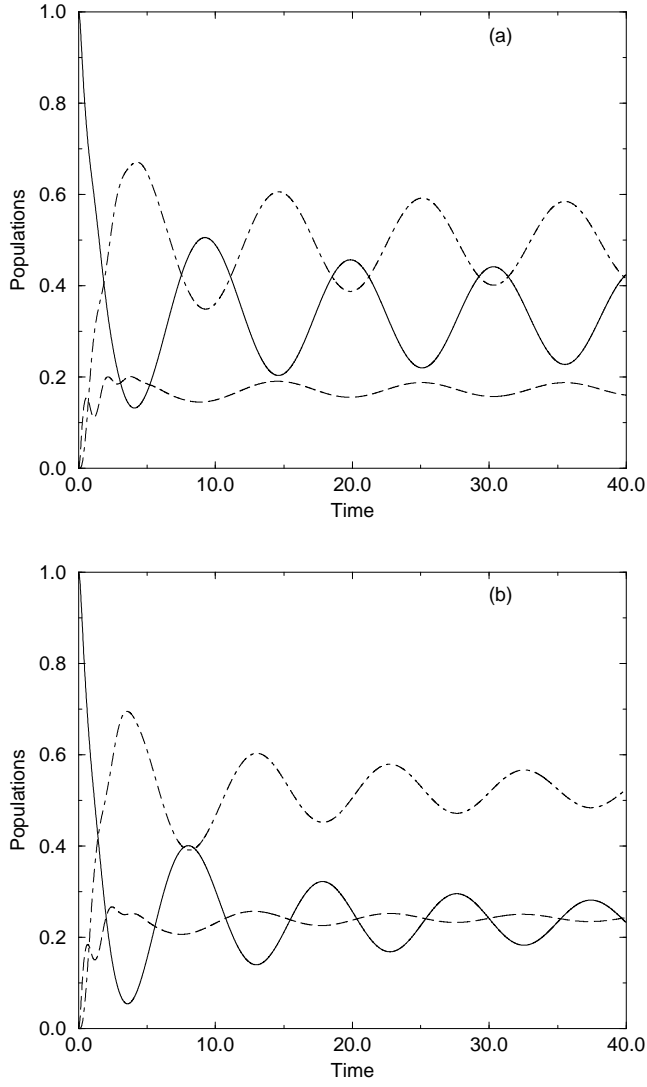
FIG. 4. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\mathcal{C}_2 = 1.5\mathcal{C}_1$, (a) $\delta_{12} = 1\mathcal{C}_2^{2/3}$ and $\delta_{23} = -1\mathcal{C}_1^{2/3}$; (b) $\delta_{12} = 2\mathcal{C}_2^{2/3}$ and $\delta_{23} = 3\mathcal{C}_1^{2/3}$. The time is in units of $\mathcal{C}_1^{2/3}$.

FIG. 6. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\mathcal{C}_2 = 1.5\mathcal{C}_1$, $\delta_{12} = -2\mathcal{C}_2^{2/3}$ and $\delta_{23} = 4\mathcal{C}_2^{2/3}$. The time is in units of $\mathcal{C}_1^{2/3}$.
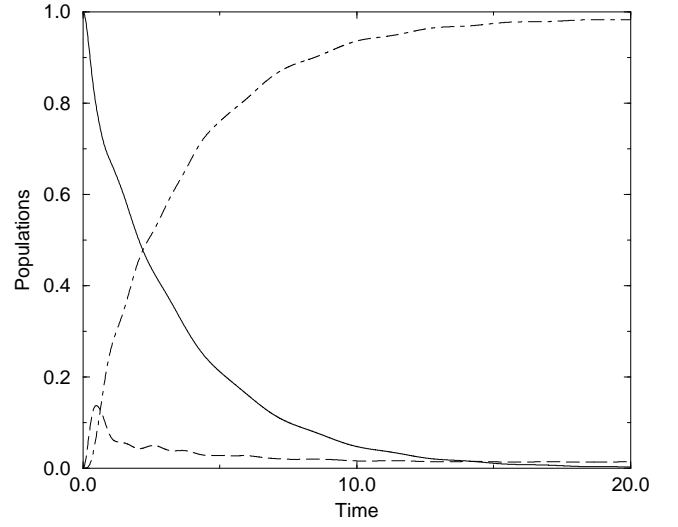

FIG. 5. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\mathcal{C}_2 = 1.5\mathcal{C}_1$, (a) $\delta_{12} = -2\mathcal{C}_2^{2/3}$ and $\delta_{23} = 2\mathcal{C}_2^{2/3}$; (b) $\delta_{12} = -2\mathcal{C}_1^{2/3}$ and $\delta_{23} = 2\mathcal{C}_1^{2/3}$. The time is in units of $\mathcal{C}_1^{2/3}$.
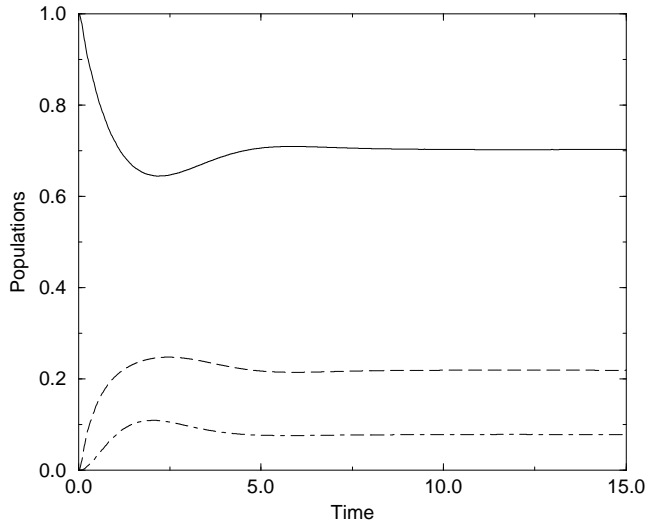
FIG. 7. The population in the atomic states as function of time. The solid line is for $|1\rangle$, the dashed line for $|2\rangle$ and the dot-dashed line for $|3\rangle$. Parameters: $\gamma_1 = 0.5\gamma_2$, $\Gamma = \gamma_2$, $\delta_{12} = 0.1\gamma_2$, $\delta_{23} = 0.3\gamma_2$ and $\omega_{up} = -\omega_{low} = 20\gamma_2$. The time is in units of γ_2.